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An indicator set for capturing long-term open space fragmentation and urban development dynamics

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ABSTRACT

Open space preservation is an important spatial policy issue in developed, densely populated countries. Understanding open space dynamics in relation to urban development is critical to the development and evaluation of such policies. Starting from a conceptual model that hypotheses how open space will have developed over the past century we use a set of landscape ecology based indicators to capture these changes from a societal (perceptional) perspective. The indicators are applied to a newly compiled geodatabase of urban development in the Netherlands to show their performance in detecting and understanding past and future trends in open space provision.

Our combined indicator set consists of land-use-based metrics that capture the area ratio of open space in relation to the total available space and total unit density of open and built-up patches. The methodology is designed to fit the low spatial and thematic resolution of land-use models as is exemplified by the inclusion of a future land-use scenario in the evaluation of open space development. The indicators confirm the hypothesised intrusion, intermediate and fill-up phases in open space fragmentation, and indicate a strong correlation between fragmentation and loss of open area. The results facilitate the distinguishing of compact urban regions from more fragmented counterparts while taking their relative state of urban development into account.

The combined indicator set is useful to summarise and compare spatial development status between regions, while in combination with the advent of more detailed historic land-use data, our approach can be used to analyse open-space dynamics in different socioeconomic contexts.

1. Introduction

The loss of open or green space is one of the most conspicuous processes of land-use change (e.g. Koomen, Dekkers, & van Dijk, 2008; McDonald, Forman, & Kareiva, 2010). In addition, dissection and fragmentation of open space have received ample policy and research attention (e.g. Bengston, Fletcher, & Nelson, 2004; Brueckner, 2000; Ewing, 1994; Irwin & Bockstael, 2004; Nechyba & Walsh, 2004). Increasingly, open space is regarded as an over-exploited, under-valued natural service-providing resource (Brueckner, 2000; van der Valk & van Dijk, 2009) that forms an essential condition for quality of life, protection of biodiversity and ecological landscape functions. Not only are the area and unity of open space affected; the character of the remaining open space is also subject to rapid change. Especially open spaces in peri-urban areas are transformed into semi-urbanised areas of public consumption (Verbeek, Leinfelder, Pisman, Hanegreefs, & Allaert, 2010).

Current attitudes towards open space are reflected in increased public demand for preservation (see Brander & Koetse, 2011). Responses exist in the form of different spatial planning initiatives that set targets for minimum amounts of open or green space per resident (e.g. 75m^2 green space per dwelling in the Netherlands, see VROM, 2006), or proposed limits to the amount of open space conversion, such as a maximum 30 ha of land consumption per day in the case of Germany (Davy, 2009; Siedentop & Fina, 2010). In fact, both the containment of urban development and the preservation of open space, alternatively termed green belt policies, constitute important themes in spatial planning in many countries (Alterman, 1997; Frenkel, 2004; Longley, Batty, Shepherd, & Sadler, 1992; Maruani & Amit-Cohen, 2007; Siedentop, Fina, & Krehl, 2015). However, demographic and other socioeconomic developments result in land-use changes that apply increasing pressure to open space in terms of remaining area per capita and quality.

To assist in this precarious planning issue, model-based simulations of land-use change can be utilised. These are particularly important for the preparation, development and ex ante evaluation of spatial policy alternatives in strategic studies (Barbosa et al., 2017; Koomen, Rietveld, & de Nijs, 2008). In order to compare the projected outcomes of specific policy interventions with their initial objectives, such studies rely on indicators that quantitatively describe land-use patterns. Changes in open space provision are typically evaluated in terms of the fragmentation of open landscapes by applying indicators derived from

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landscape ecology, which essentially follow an ecological perspective. Such indicators usually capture the scattered growth in built-up areas or the fragmenting of open spaces into smaller units or patches (e.g. Frenkel & Ashkenazi, 2008; Jaeger & Schwick, 2014; Schneider & Woodcock, 2008; Siedentop & Fina, 2012). The most extensive study carried out on landscape fragmentation in Europe (European Environment Agency, 2011), for example, described the transformation of open space patches into smaller and more isolated ones through measuring landscape connectivity using the effective mesh size indicator developed by Jaeger (2000), which is sensitive to the fragmenting impact of road infrastructure. For a focus on the human appreciation of open spaces, this straightforward approach is not very helpful because of the ambiguous relation that the cultural services offered by open spaces have with infrastructure: roads increase the accessibility of open spaces but may decrease their quality when they are large or intensively used. Similar differences between ecological and human-centred views are also noted by Verbeek and Tempels (2016) who point out that depending on the chosen perspective the fragmentation effects of similar landscape elements can be very different.

The ecological origin of these indicators implies that they miss a societal perspective, which relates to the way most people perceive changes in their environment (Di Giulio, Holderegger, & Tobias, 2009). This is relevant because the human requirements for open space -differing between cultures and specific living conditions- are far less demanding in terms of location, size and connectivity than for instance the ecological requirements for maintaining or improving biodiversity (see e.g. Donaldson, Wilson, & Maclean, 2017; Hanski, 2015; Wilson et al., 2016). It has to be acknowledged, however, that perspectives on the ecological responses to habitat fragmentation as a pattern versus habitat loss as a process are the subject of fierce academic debate (see e.g. the review by Fahrig, 2017). Regardless of the developments in landscape ecology, empirical studies have acknowledged that open space within the built-up city limits (typically of low ecological value) is considerably more important to the urban population than open space at the urban fringe (Brander & Koetse, 2011; Nechyba & Walsh, 2004). Furthermore, most indicators that evaluate the impact of urban sprawl on open spaces (e.g. the 'Effective open space' indicator in Siedentop & Fina, 2012) assign greater weight to larger areas based on their potential to sustain stronger and more diverse populations of different species. This lack of recognition of smaller open space units is referred to as "the fragmentation bias of open space" by Dewaelheyns, Vanempten, Bomans, Verhoeve & Gulinck (2014, p. 439).

The main objective of this study is to propose an effective set of indicators able to capture long-term open space development from a societal perspective. The indicator set aims to distinguish different stages in the process of open space loss in urban agglomerations based on observed and simulated land-use configurations that can, for example, be applied in ex ante evaluations of (spatial) policies that are likely to affect urban development patterns. For this study, we choose a policy-relevant, societal (human-centric) perspective on open space that relates to aesthetical, mental/social/physical health and recreational values through its provision for activities. Although the exact composition and structure of the landscape matters to people, the societal value of landscapes is, in our view, primarily determined by the presence or absence of certain types and amounts of land use. Therefore, a relatively simple land-use-based indicator that is of limited value for reflecting ecological values can be used to reflect basic societal value. To some extent our efforts mirror the attempts to build urban sprawl indicators. A wide range of indicators has been proposed to capture this contested issue stressing low-density urban developments that result in spread out non-compact urban forms (e.g. Frenkel & Ashkenazi, 2008; Mubareka, Koomen, Estreguil, & Lavalle, 2011; OECD, 2018; Schwarz, 2010). Our approach is different in the sense that we focus on the impacts of urban development on the remaining open spaces, which is more comparable to the way Verbeek and Tempels (2016), for example, evaluate the fragmentation of open space in Belgium (Flanders) from a spatial planning perspective. As such our approach is more closely related to planning efforts that try to preserve open space rather than contain urban development.

To show the operation and performance of the indicator set, we apply it to a geodatabase of urban development that we have specifically developed for this study. As a case study area we select the Netherlands, a country that has experienced extensive urbanisation in the past century and where the provision of open space represents an important spatial policy issue. The results presented in this study document the long-term process of open space development and offer a reference point for the evaluation of potential future changes. Thus, they allow for the comparison of projected open space dynamics within and between regions and hence provide input for local spatial policy evaluation and development.

2. Hypothesising open space dynamics

The transition from open to urban space takes place in the continuum from totally open or natural space to totally urban built-up space. The fragmentation processes that are involved in this transition are described by Antrop, van Damme, Dhondt, and Matthysen (1994) and Gulinck, Meeus, Bomans, Dewaelheyns, and Heremans (2007) as: dissection (by infrastructure and other linear barriers), densification (more houses, infrastructure and other built-up elements per km^2) and congestion (progressed densification typical of the peri-urban network with remaining fragments of open space). A more extensive, visual description of the fragmentation of natural areas is provided by Forman (1995) and Jaeger (2000), which we adapt to the fragmentation of open space. In Table 1 we use arrows to indicate the direction of change in the number of open and built-up area units and the total area of open space associated with the different processes that lead to open space fragmentation. Several fragmentation processes can be recognised by specific combinations of quantitative changes in the number and area of spatial units.

If we combine the concepts of matrix (the most extensive and well-connected landscape type) and network by Forman and Godron (1986) with the landscape fragmentation phases distinguished by Jaeger (2000), and apply this to open spaces, we can distinguish three different transition phases that correspond to the fragmentation phases in Table 1. In the first intrusion phase, open space remains the dominant landscape element (the matrix), while in the subsequent intermediate phase open space is progressively dissected by infrastructure and is isolated by built-up space. In the third fill-up phase, the built-up areas extend further and form the matrix of the landscape.

Although the indicated transformation processes can occur simultaneously, it can be expected that each successive transition phase will be dominated by a specific fragmentation process (Jaeger, 2000). Another expectation is that the number of built-up area units will initially increase faster than the number of open units, whose formation is contingent on the coalescence of built-up area units and dissection by infrastructural development. Our assumptions regarding long-term open space development are depicted in Fig. 1. With ongoing urbanisation, however, we can expect that at a certain point in time the number of built-up area units will drop owing to the merging of growing individual built-up areas. While the number of built-up area units drops, the number of open space units continues to increase due to accelerated inclusion and dissection processes. In the final fill-up phase we can expect a further decrease in the number of built-up areas and a decrease in the number of open areas because some small remaining open areas will urbanise entirely. Thus, we expect that the total number of open and built-up area units is a good indicator for the transition phase of open space at a certain point in time if it is used in combination with information regarding the area of remaining open spaces.

Of course this stylised, conceptual representation of open space development will in reality be somewhat erratic, owing, for example, to

Table 1
Overview of different processes that lead to open space fragmentation. Open space in white, built-up space in dark grey (modified and extended after Forman, 1995 and Jaeger, 2000). Arrows denote increase (↑), decrease(↓) or no change (-) in number of built-up and open space units and total open space area.

	Nr. built-up area units	Nr. open units	Area open space
Intrusion	↑	-	↓
Incision	-	-	-
Dissection by infrastructure	-	↑	-
Dissection by built-up structure	↓	↑	↓
Isolation / inclusion	↓	↑	↓
Shrinkage	-	-	↓
Fill-up	-	↓	↓

changes in the rate of urbanisation, alternating periods of urban densification (brownfield development) and diversification (diffuse residential and commercial/industrial sprawl). Moreover, the spatial extent of the study area will affect these curves since larger study areas will include more zones at different stages of development.

In a similar vein, we can also hypothesise about changes in the total area of open space. Given that almost all open space fragmentation processes lead to a reduction in the amount of open space, we expect to see a continuous decline in open space, the speed of which depends upon prevailing economic and demographic developments.

3. Case study area

The preservation of open space through concentrated urbanisation has formed a major spatial planning objective in the densely populated Netherlands since the late-1950s (Koomen & Dekkers, 2013; Rietveld & Wagtendonk, 2004; van der Burg & Dieleman, 2004; Zonneveld, 2007). Notwithstanding the relative success of these policies in retaining distinct, compact metropolitan urbanisation patterns (EEA, 2010) and limiting urban development in specific, protected regions (Koomen, Dekkers, & van Dijk, 2008), large parts of the characteristic open agricultural landscapes in the Netherlands were lost or disturbed by different types of land-use transformations. These land conversion processes have led to a doubling of the urban area in the second half of the 20th century (VROM, 2001), rendering large, non-built areas more scarce. Both the total consumption of rural land (in area) and development speed (area/year) in recent periods (e.g. between 1990 and 2000) are among the highest in Europe (Siedentop & Fina, 2012), and different land-use modelling scenarios indicate that over the course of the following 30 years this urbanisation trend will continue (CPB/PBL, 2015). The methodology we introduce in this paper seeks to show areas where open space has been lost and how this has affected the local balance between open and built-up areas. It thus highlights specific regional developments rather than averaged national developments.

For our spatiotemporal analysis of open space development in the Netherlands, we distinguish three main regions that differ in terms of population size and regional economic performance (Randstad, Intermediate zone and Periphery in decreasing order of economic performance and population size). The results of our analysis are summarised for these three zones to highlight differences in development stage. In addition, we select 30 non-overlapping rectangular sample areas (14 × 14 km) around historical city centres to show the potential of the indicators to capture local dynamics. The sample areas are approximately equally distributed throughout the three regional zones

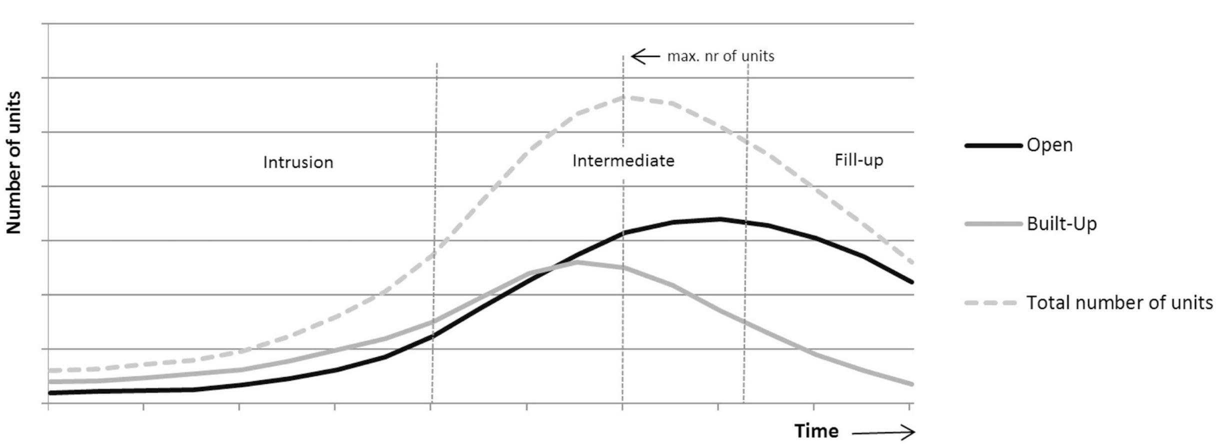

Fig. 1. Expected general trends in number of open space and built-up area units.

Table 2
Number of inhabitants and population classes of selected sample areas (Source population data: see Appendix A).

Rank nr.	City / town	Regional zone	Population core city 2010	Regional statistics (totals 2010)			
				Zone	Area (km2)	Population	Pop. / km2
1	Amsterdam	Randstad	767,457		5922		
2	Rotterdam	Randstad	593,049	Randstad		6,742,280	1139
3	Den Haag	Randstad	488,553		15,294		
4	Utrecht	Randstad	307,081	Intermediate		6,330,055	414
5	Tilburg	Intermediate	204,853		13,777		
6	Almere	Intermediate	188,160	Periphery		3,453,910	251
7	Groningen	Periphery	187,298				
8	Nijmegen	Intermediate	162,963				
9	Apeldoorn	Intermediate	155,726				
10	Haarlem	Randstad	149,579				
11	Maastricht	Periphery	118,533				
12	Leiden	Randstad	117,123				
13	Ede	Intermediate	107,756				
14	Leeuwarden	Periphery	94,073				
15	Alkmaar	Intermediate	93,861				
16	Hilversum	Randstad	84,573				
17	Oss	Intermediate	77,392				
18	Lelystad	Intermediate	74,628				
19	Gouda	Randstad	71,122				
20	Assen	Periphery	66,857				
21	Middelburg	Periphery	47,997				
22	Harderwijk	Intermediate	44,010				
23	Hellevoetsluis	Randstad	39,756				
24	De Ronde Venen	Randstad	34,400				
25	Meppel	Periphery	32,378				
26	Deurne	Intermediate	31,526				
27	Ooststellingwerf	Periphery	26,235				
28	Anna Paulowna	Periphery	14,234				
29	Zederik	Randstad	13,397				
30	Doesburg	Intermediate	11,600				

and over a range of population size classes from approximately 10,000 to 750,000 inhabitants (in their central municipality in 2010). The use of equally sized and shaped sample areas allows for unconstrained characterisation and comparison of urban areas, similar to the approach of Siedentop and Fina (2012). The selected sample areas and population totals of their central city or town are displayed in Table 2 and Fig. 2.

4. Methodology and data preparation

The methodology we apply follows three consecutive steps that are described in the following subsections: spatial data selection and processing; definition of the indicator set; and construction of the geodatabase and indicator implementation. First, however, we elaborate on our definition of open space.

We deem open space to refer to all territorial space of the Netherlands that is not covered by built-up structures. Our definition of open space includes open (agri)cultural space and open green/natural space (forests, parks and other natural areas such as wetlands and lakes). Special attention is given to infrastructure. While roads and railways in general provide access to open space and may not (or only partially) visually dissect the open landscape, larger and more intensively used infrastructure can fragment the open landscape. Large infrastructure can block access to parts of the landscape, separate neighbourhoods and have a negative impact on important amenities within the open landscape, such as fresh air and silence (Chiesura, 2004; Verbeek & Tempels, 2016). In this respect they "reduce the restorative effect of everyday landscapes" (Di Giulio et al., 2009, p. 2963). We therefore exclude the intensively used national road infrastructure from our definition of open space. The national road infrastructure concerns the main road network under the responsibility of the national authorities. The network is comprised of motorways and major roads that most often consist of 2 × 2 lanes and speed limits of 100 km/h or more.

A major challenge in our analysis of long-term open space development is the limited spatial and attribute resolution of land-use data from historical data and simulation models. Spatial indicators or landscape metrics and underlying landscape patterns are known to be highly sensitive to scale-related aspects of data quality, such as resolution and extent (Antrop & van Eetvelde, 2000; Turner, Dale, & Gardner, 1989). Therefore, an important component in our study is the construction of a consistent geodatabase to evaluate the indicators' performance in describing historic, urban and open space development patterns. We supplement this database with a scenario-based simulation of future land use to illustrate the ability of the indicator set to capture the impact of potential future urbanisation patterns on open space provision.

4.1. Spatial data selection and processing

We collect raster-based historical land-use data for the years 1900, 1930, 1960, 1970 and 1980 on a 50 × 50 metre resolution, and we collect vector-based historical land-use data on a 1:10,000 scale for 1989, 1996, 2000, 2006 and 2010 from various sources (Appendix A). Next, we reclassify both types of data to built-up or open land using the reclassification scheme provided in Appendix B. Through detailed comparisons and the production of differential charts, we have found a number of inconsistencies pertaining to known differences in classifications and scales between different years (see Appendix A). For example, some relatively small areas (mostly < 5 ha) that were classified as built-up before 1996 are revealed as open areas on more recent maps. As such conversions are extremely rare, we assume they result from classification issues and the application of more detailed base data. In the 1980 land use map, for example, relatively small, elongated villages along roads, that were part of a combined urban area and infrastructure class are often classified as infrastructure in the 1996 dataset. Such loss of urban area does not refer to actual changes (these

Fig. 2. Locations of 14 × 14 km sample areas.

villages still exist) and have been corrected. Therefore, we harmonise the different years until 1996 by replacing built-up areas with open space in older datasets where these areas consisted of open area in post-1996 datasets. This correction affects 1200 ha (0.045% of the built area in 1980) so the amount of error resulting from the harmonisation process is limited compared the actual amount of land-use change occurring in the large time span between the different datasets.

In order to further limit potential small errors introduced by mapping differences, we remove all map units with open or built-up space smaller than 1 ha. These errors may result from differences in map resolution combined with different overlay and raster-vector conversion operations that can easily produce data artefacts such as polygon slivers (Dewaelheyns et al., 2014). Consequently, this study does not indicate open space fragmentation processes concerning units smaller than 1 ha.

The land-use data referring to 2040 is taken from the Land Use Scanner simulation model that is applied in numerous spatial planning related studies in the Netherlands and beyond (e.g. Hoymann, 2011; Koomen, Koekoek, & Dijk, 2011; Lavalle et al., 2011; Te Linde, Bubeck, Dekkers, De Moel, & Aerts, 2011). The model simulates future land-use patterns based on scenario-specific assumptions related to a regional land demand for specific types of use and a local assessment of suitable locations for these developments. The simulation process follows a logit-based approach that allocates land to the most suitable locations under the constraints of demand and available space (Koomen, Hilferink, & Borsboom-van Beurden, 2011). The selected Global Economy scenario depicts land use according to a future in which deregulation, economic development and population growth prevail (De Moel, Aerts, & Koomen, 2011; Riedijk, Wilgenburg, & Koomen, 2007). From an open space preservation perspective, this can be considered a worst case scenario as it assumes a fairly large increase in population (growing by about 4 million inhabitants to reach 20 million in 2014; in line with developments over the past 30 years) and limited planning restrictions on urban development. Obviously, we could include many other scenarios to test the impact of alternatives scenarios or policy alternatives. To keep our focus on understanding past, observed trends in open space provision, however, we only use the future scenario as an illustration of possible changes, leaving a detailed exploration of future developments to other, dedicated studies. Future land use is mapped at a lower spatial and attribute resolution (15 classes). We do not consider the coarser resolution (100-m instead of 25-m grid cells) as a major problem due to the removal of all spatial units smaller than 1 ha. The mixed land-use class of urban area in the scenario maps, which lumps local roads, water surfaces and different type of open spaces such as parks, public gardens and sport fields together with built-up areas, is more problematic for our analysis. For specific unlikely land-use transitions that appear via the comparison of this more aggregated definition of future urban land with the stricter defined built-up areas of earlier years (e.g. the disappearance of historic parks or motorways), we apply dedicated correction procedures (see Appendix B for details).

In order to create a generalised layer representing a connected urban fabric that is not interrupted by narrow linear spaces (e.g. spaces occupied by roads and canals up to a maximum width of 100 m), we carry out two consecutive buffer operations on the built-up area layers: a positive 50-m buffer with all borders dissolved to fill up internal linear spaces, followed by a negative 50-m buffer operation to remove the undesired buffer zone added outside the original built-up area. A similar approach was applied by the former Ministry of housing and spatial planning to define the contiguous urban areas in which urban development was preferably concentrated (Odijk, Van Bleek, & Louwerse, 2004). The 2040 land-use scenario data with its lower spatial and attribute resolution is generalised slightly differently in order to allow comparison with the observed 2000 land-use map. See Appendix B for operational details on this process.

4.2. Defining open space development indicators

In order to describe open space dynamics, we use specific versions of two spatial metrics commonly applied in landscape ecology: PLAND (percent of landscape) and PD (patch density). To distinguish them from their landscape ecological counterparts we name these metrics open space ratio (OSR) and total unit density (TUD). These are defined as follows:

$$\text{OSR} = \text{Open Area}/\text{Total Area} \tag{1}$$

$$\text{TUD} = (\text{Number of Built-up area units}+\text{Number of Open Spaces}) * 100 /\text{Total Area} \tag{2}$$

where Open Area represents the summed area of all open space units within the analysis area (both in km^2) and Total Area the size of the analysis area in km^2. OSR is expressed as a dimensionless fraction, while TUD is presented as the number of units per 100 km^2 to arrive at values ranging from 0 to 50 (depending on the characteristics of the area and applied data sets). We consider TUD a simple indicator for the fragmentation of open space (into more and on average smaller patches) as it reflects both the degree of intrusion of open space by built-up area units larger than 1 ha and the dissection and/or inclusion/isolation of open space represented by the number of open space units larger than 1 ha.

To calculate the area and count the number of separate built-up area units and open space units consisting of adjacent grid cells of the same class (see Appendix C), we follow a raster-based procedure using GIS. The raster procedure has two advantages. It allows for faster computation and applies a uniform method that better matches the human (visual) perception of open space to distinguish between separate open and built-up areas based on connecting grid cells. In this procedure, open space units are separated by national highways and adjacent built-up grid cells perpendicularly or diagonally connected to one another ('Moore neighborhood'). In this way, we simulate a visual perception of separated open spaces, even if in reality small physical connections between open spaces remain possible.

4.3. Development of a historical geodatabase of spatial fragmentation

In order to produce a historical map series showing the local development of open space linked to individual fragmentation processes, we make spatial unions and selections using the original vectorised and reclassified map layers of open and built-up space and the separately produced map layers containing the generalised units of built-up and open space. For example, areas of existing open space that were fragmented and isolated by new built-up space are created as new polygons in the geodatabase and labelled with the year of isolation. Unless these isolated open space units were transferred to built-up space, these polygons retain their classification as isolated open space in the year of isolation in the layer unions of subsequent years.

Accordingly, we classify polygons representing new built-up space, new open space (e.g. formed by land reclamation) or new dissected open space (by infrastructure) with the corresponding code and year of creation. The remaining polygons with unchanged land use maintain their codes and years of creation. We create separate map classes for isolated built-up spaces and filled-in open spaces. We use the map class 'isolated built-up space' to indicate dispersed urban development, being new built-up space developed at least 500 m from existing built-up space.

The historical geodatabase can be used to map local spatial developments. These detailed map-based representations allow the calculation of four indicators that can be used to characterise developments in specific regions (expressed as unit density per 100 km^2):

- Unit density new Isolated Open Space
- Unit density new Dissected Open Space
- Unit density new Isolated Built-Up Space
- Unit density Connected Built-Up Space

The spatial distribution of the different map classes can be displayed chronologically. In this way, the development of spatial fragmentation can be visualised over time and the total numbers and areas of the different fragmentation classes can be evaluated, in order to see how they contribute to the combined graphical indicator of open space development discussed in this paper. The geodatabase can be accessed via: https://hdl.handle.net/10411/T9PLUL.

4.4. Visual and comparative analysis of open space development

The indicator set described in the preceding sections is used for visual and comparative analysis at different spatial scales. Cities of different population sizes are aggregated into population size classes for further analysis. Additional statistical data regarding population growth and household size between 1900 and 2010 are added to place the spatial development data in a larger perspective. We apply line smoothing between the indicated data observation points in all graphs displayed in this document to support their visual interpretation.

5. Results

5.1. Open area ratio

Open space shares steadily declined from 1900 until around 1960, with greater decreases in the case of the Intermediate and Randstad zones (Fig. 3). Between 1960 and 1990 the loss of open area accelerated, especially in the Randstad. In the mid-1990s the open area loss slowed in all regions, but accelerated again after 2010 in the Randstad zone according to the simulated urban development in the Global Economy scenario for 2040. Open space loss cannot be linked to regional changes in population alone. The strong increase in population in the first part of the 20th century did not directly lead to substantial loss in the Randstad, while the slower growth rates of the 1970s in the Randstad correspond to a substantial loss in open space.

5.2. Total unit density

The temporal dynamics of the combined density of open and built-up area units per 100 km^2 represented in Fig. 4 shed light on different aspects of the urban development process of the last century. In the presented regions, growth figures accelerated between 1960 and 1970, followed by a second acceleration period between 1980 and 2000. Unit densities and growth figures were highest in the Randstad area, indicating its more fragmented landscape.

The impact of urban development on open space fragmentation in the urban agglomeration around the largest city in the Netherlands is highlighted in Fig. 5 that shows the long-term trend in total unit density

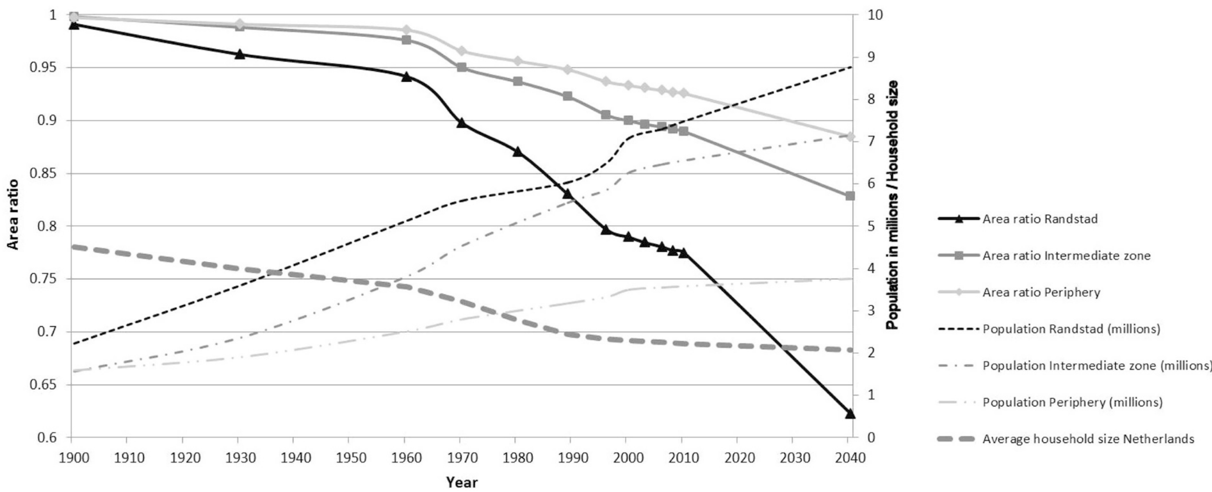

Fig. 3. Open space area ratios and population totals by region and average household size in the Netherlands, 1900–2040 (Global Economy scenario).

and its two constituent parts (the densities of open and urban units). After the number of built-up area units started to decline (by interconnection) around 1980, the number of open space units stabilised around the year 2000. The simulated land-use patterns for 2040 show a further decline in built-up area units and increase in open space units (by isolation and dissection), and thus suggest that the urban agglomeration process will continue.

5.3. Combined indicator open space area ratio/total unit density

The combined area ratio/unit density indicator for the whole country and its three main regions is plotted in Fig. 6. The graph shows that the regions follow the same general trend, but with different speeds of development. The speed of fragmentation and loss of open space is highest in the Randstad area, especially during the main period of highway construction between 1960 and 1996. After 1996 the Randstad followed a more compact development path compared to the other regions. Fragmentation in the peripheral region follows a slower pace and development is also a bit more dispersed. After 2010, the Global Economy scenario for 2040 indicates a continued loss of open area for all regions, but with a less dispersed character for the Randstad.

In addition to showing open space dynamics over time, the combined indicator can also be used to depict the relative state of open space availability for individual cities or regions at a specific moment in time (Fig. 7). We find a strong relationship ($R^2 = 0.92$) between open area ratio and spatial unit density for the 30 sample areas. This relationship is depicted by the dashed line in the graph and indicates that the samples cities and towns on average have a more fragmented appearance (have higher numbers of open space and built-up area units per 100 km^2) when their total amount of open space is lower. Note, for example, that the most populous cities (with rank numbers 1 to 4 in Table 2) are found in the lower right corner of the graph. More interestingly, the combined area ratio/unit density indicator can also be used to distinguish the more compact cities (below the dashed line) from their more fragmented counterparts (above the dashed line). The city of The Hague (rank number 3) is thus shown to be more compact than the other cities in the population top five. Also the less populous towns can be differentiated in more fragmented (e.g. numbers 22 and 23) and less fragmented ones (e.g. 26 and 27).

5.4. Detailed scale level indicator

A detailed analysis of spatial fragmentation processes using the historical geodatabase shows several trends that are not clearly visible

Fig. 4. Total unit densities per 100 km^2 by region.

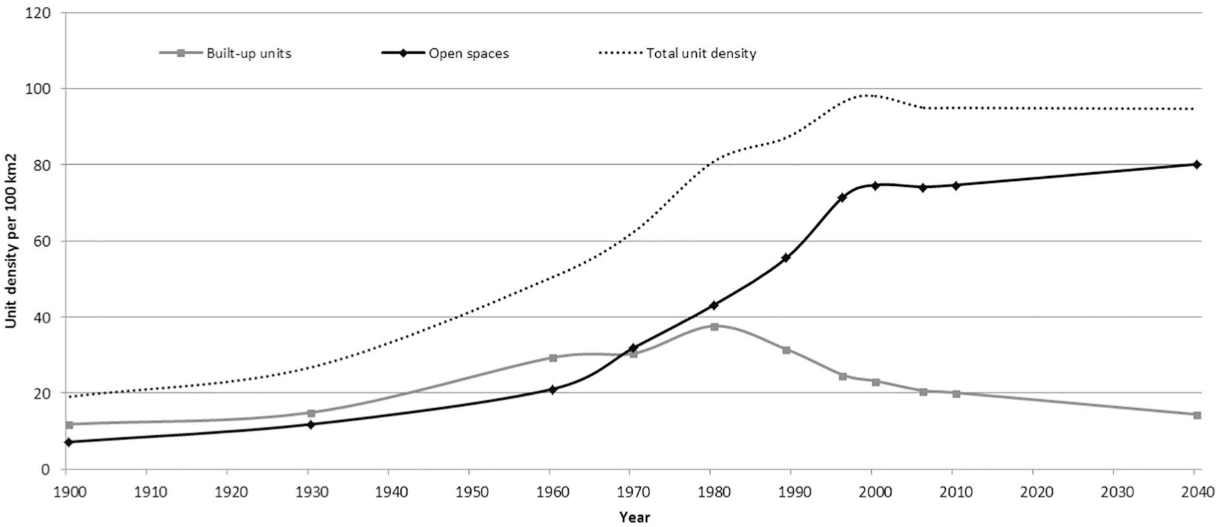

Fig. 5. Densities in open and built-up spaces and total unit density for the urban agglomeration around Amsterdam.

in the generalised analysis with the combined indicator set. Three distinct waves of urban development can be distinguished in Fig. 8: in the pre-war period between 1900 and 1940, and in shorter periods around the 1970s and 1990s. The large proportion of dispersed built-up area units of the total urban development in the 1930s is particularly noteworthy. Subsequent to this period, the proportion of isolated built-up area units decreased gradually, indicating a shift to more compact urban development.

The main trends in urbanisation during the past century are summarised in Fig. 9 that shows the number of new isolated and new connected built-up spaces for each time period. New urban development was most dominant in the western part of the country before 1930, subsequently concentrated in the south-east until 1960, and was omnipresent in the following decade. From 1970 on, built-up areas became more connected and the development of new areas slowed down.

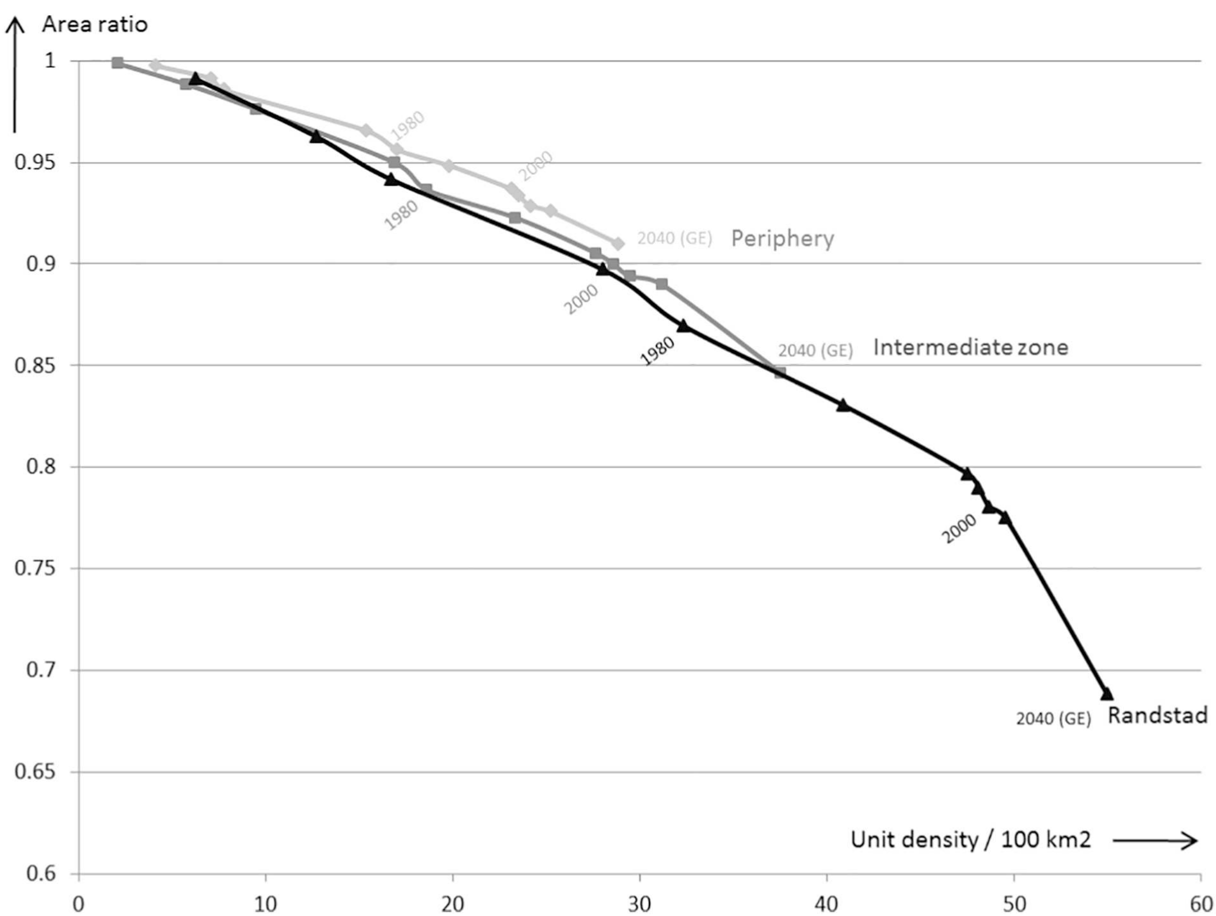

Fig. 6. Combined representation of open space area ratio and unit density indicators, 1900–2040 (Global Economy scenario). The relative speed of development can be inferred from the distance between the observed or simulated values (indicated by the dots).

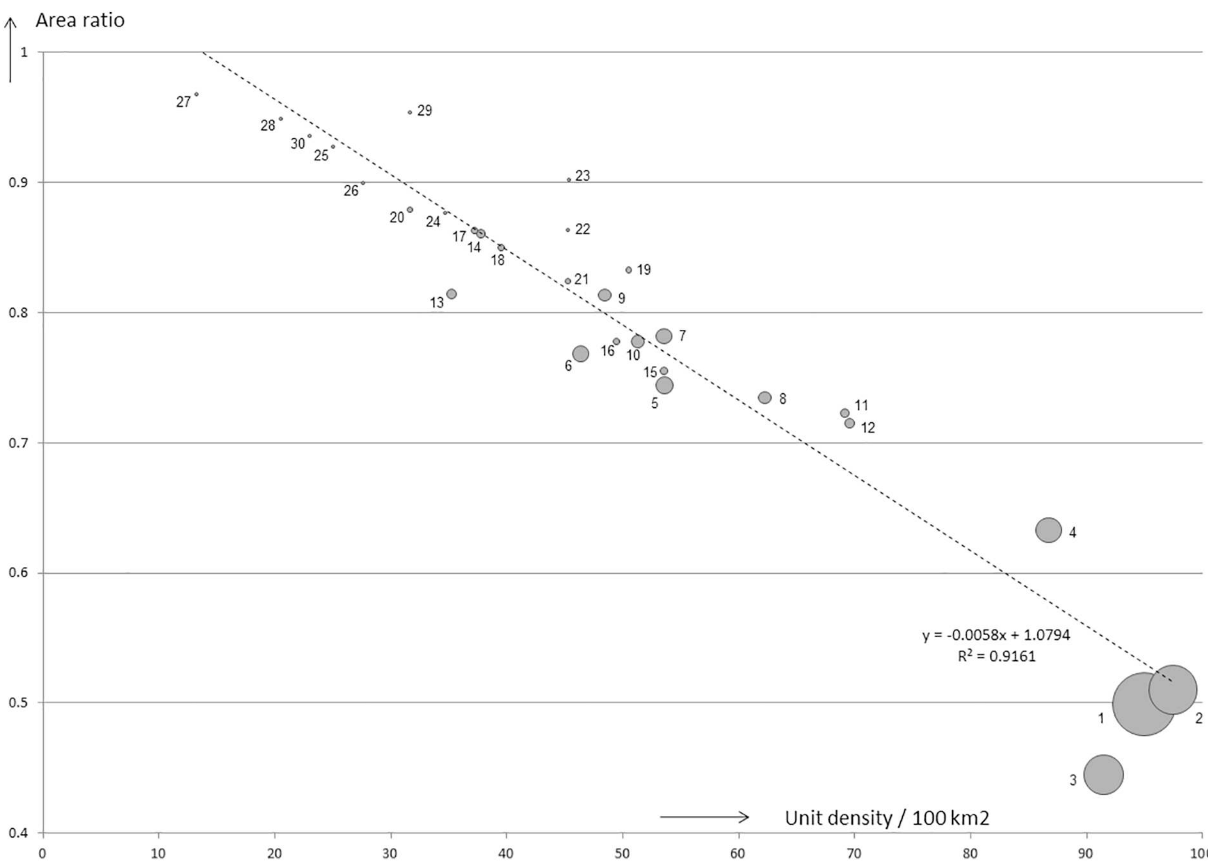

Fig. 7. Combined area ratio/unit density indicator for 20 city regions in 2010. Rank numbers and proportional symbols refer to the city population rank and number listed in Table 2.

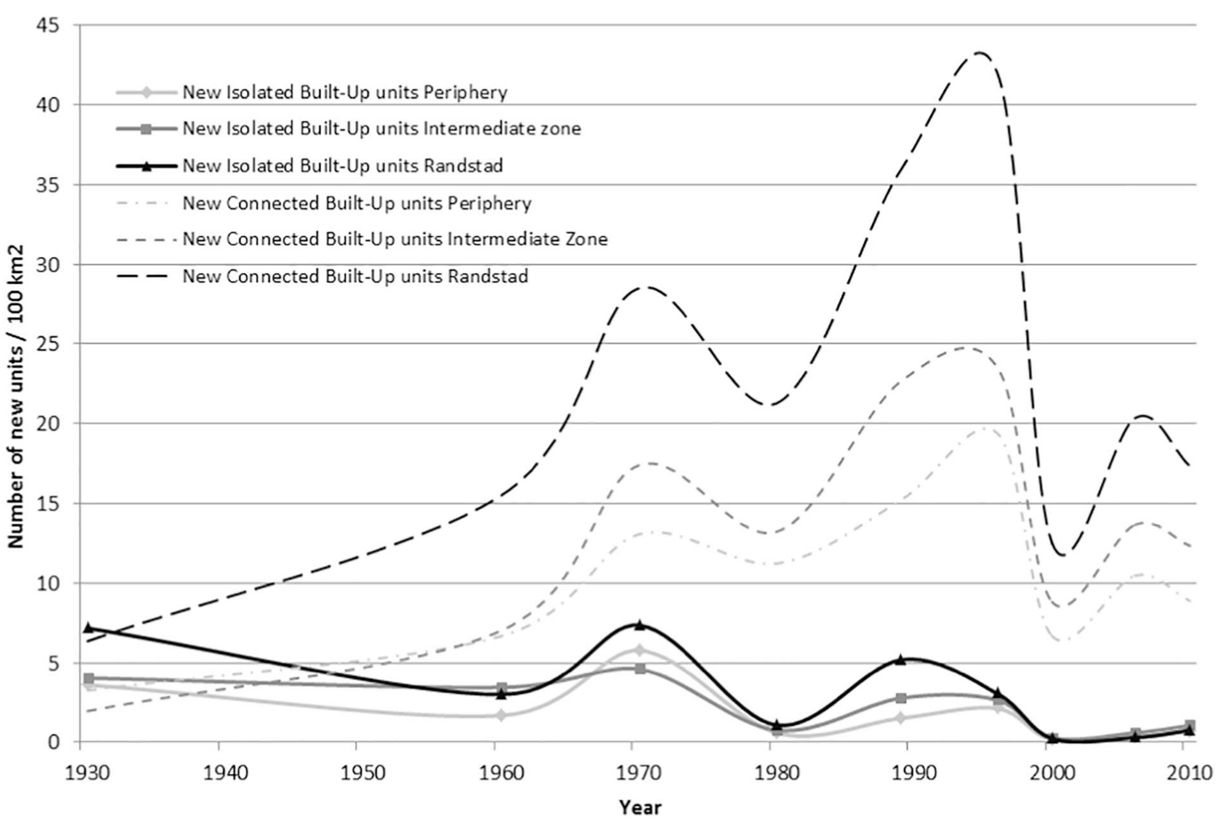

Fig. 8. Number of new isolated and connected built-up area units per region/100 km^2.

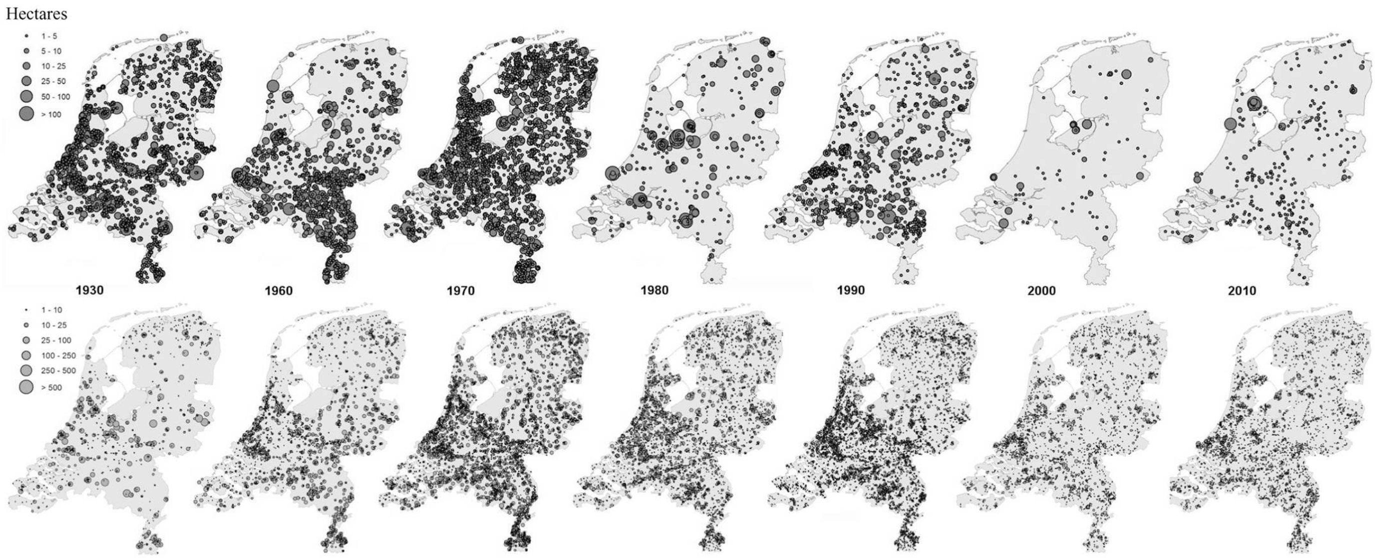

Fig. 9. New isolated (above) and new connected (below) built-up space developed between 1900 and 1930 (left) and subsequent periods. Circles represent the size of individual built-up spaces in hectares in 6 classes.

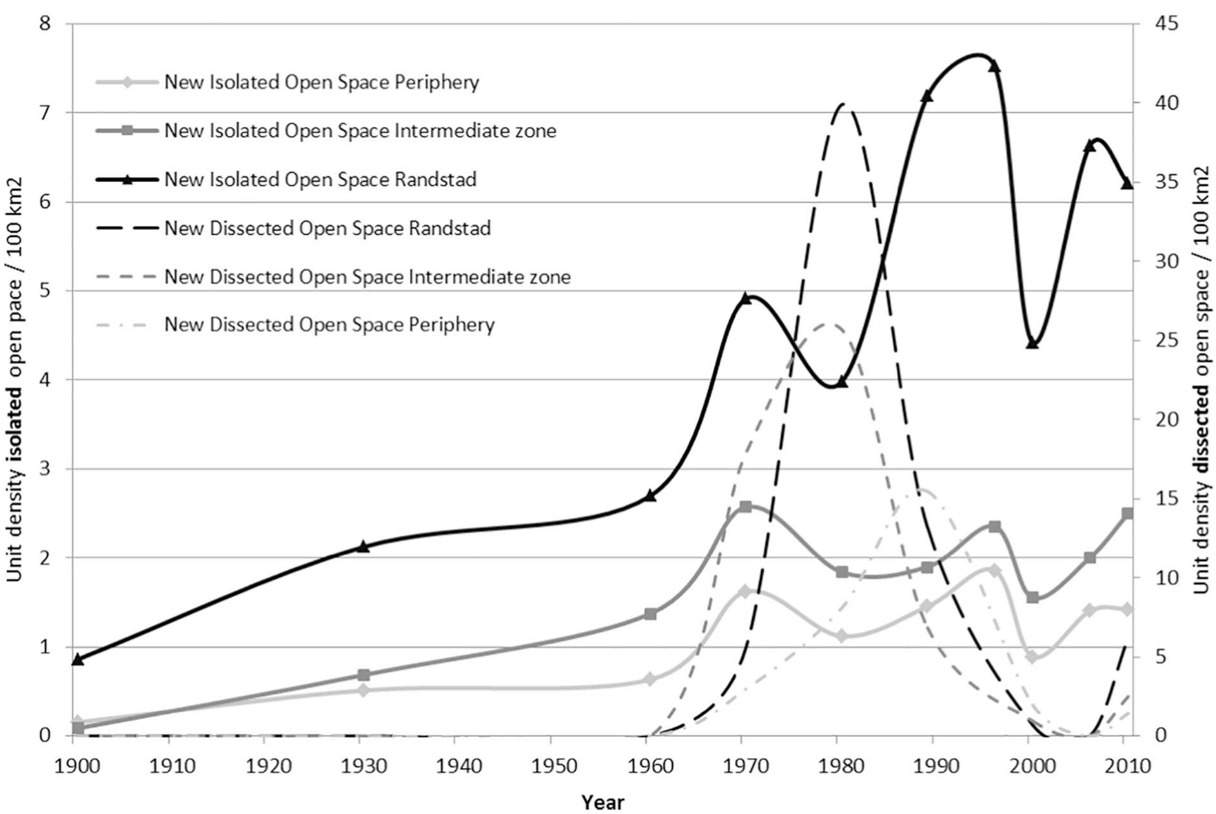

Fig. 10. Unit density isolated and dissected open space per region/100 km^2.

The fragmentation processes of dissection and the isolation of open space are depicted in Fig. 10. The dissection of open space seems to follow the massive extensions of the national road infrastructure after 1960, while the different phases with peaks of new isolated open space units coincide with or follow shortly after the relatively high values for new isolated built-up area units shown in Fig. 8.

6. Discussion and conclusions

This study describes the potential of an indicator set, operationalised with an extensive geodatabase of built-up area patterns, to capture open space dynamics. We have developed several indicators to analyse urban development in the Netherlands from 1900 to 2040 at different spatial scales. The obtained application results can be linked to known historical developments. For example, the rapid loss of open area between 1960 and 1990, especially in the Randstad, hints at large-scale, post-war suburbanisation and urban expansion processes. Furthermore, the larger population growth and slower open space loss in the Randstad in the early part of the 20th century and the slower population growth in the 1970s that was accompanied with a substantial open space loss, can at least partly be explained by the relatively fast decline in household size during that period (also shown in

Fig. 3). This can also be related to the construction of other, more land-intensive types of housing. In a more advanced state of urban development, a stabilisation or even decrease of unit density can be expected following the coalescence of ever-larger urban areas in which new open space units are included and former open spaces are filled up. This hypothesised behaviour as depicted in Fig. 1, is observed in the spatiotemporal dynamics in the numbers of built-up area units and open space units in the most urbanised areas of the country. This behaviour is also confirmed by the decrease in unit density after 2010, suggesting that the future landscape will be characterised by fewer and larger urban spaces that also claim part of the remaining open spaces. While this result is a simulation outcome that follows from scenario-based assumptions, it shows how informative a time series of straightforward indicators can be, warning policymakers about the potential implications of future developments.

The combined indicator shows that both aspects of urban development are strongly correlated: fragmentation is stronger (characterised by a larger number of open spaces and urban units) when the open space area fraction is lower. This general trend can be used to distinguish more compact regions from their more fragmented counterparts, while taking their relative state of urban development into account. The observed diversity in compactness of the less populous cities may relate in part to local physical conditions (bordering a sea or river), the composition of the built-up area (e.g. presence of large-scale industry and types of residences) or spatial planning restrictions (e.g. related to nature conservation or national buffer zones, see Koomen & Dekkers, 2013).

Finally, the spatial datasets contained in the historical geodatabase of spatial fragmentation can be used to visualise and help explain the combined indicator results obtained at a coarser scale, and to link these to actual and historical land-use processes. This database is published online and can be used for further spatiotemporal analysis of fragmentation processes in the Netherlands. We notice, for example, the proportional decrease of isolated built-up area units in the period following the 1930s in which dispersed built-up area units formed a relatively large share of the total urban development. This indicates a shift to more compact urban development, potentially caused by a growing lack of development space outside of the existing built-up area. Other options include studying the possible effects of specific local, regional or national spatial policy in combination with economic and societal trends.

The developed indicator toolset focuses on the societal rather than, for example, ecological relevance of open space. It acknowledges open spaces irrespective of their size and prioritises visual aspects of open space over, for example, physical landscape ecological aspects, such as landscape connectivity and patch border length. This way it can be used to evaluate the impacts of different urban development scenarios on the provision of open space, which represents an important spatial policy issue in many countries (e.g. van der Valk & van Dijk, 2009). Our indicator toolset does not suffer from the “fragmentation bias of open space” discussed by Dewaelheyns et al. (2014) as it does not apply greater weights to larger open spaces, but we acknowledge that some fragmentation bias of open space remains, as we exclude the spaces smaller than 1 ha from our analysis.

As the proposed indicators also work well with spatiotemporal data of relatively low spatial and attribute resolution, they can be based on land-use modelling results with relatively coarse resolutions that are produced by research agencies to inform spatial planners (Barbosa et al., 2017; Jacobs-Crisioni, Diogo, Perpiña Castillo, Baranzelli, Silva, Rosina, … & Lavalle, 2017; Van Duinen, Rijken, & Buitelaar, 2016). The presented case study includes simulated urban development patterns for one socioeconomic scenario, but a range of alternative future scenarios could be included, referring to, for example, different demographic or socio-economic developments. The indicator set can also be used to assess the impacts of specific spatial policies on the local fragmentation of open space or their contributions to fostering more compact urban development. The combined open space area ratio and total unit density indicator is especially useful to assess the latter type of impact, which is usually difficult to describe as the commonly applied shape-related metrics (such as the circularity ratio that expresses the degree to which a shape resembles the most compact possible form: a circle) fail to fully acknowledge the importance of size differences in urban areas (Ritsema van Eck & Koomen, 2008). In addition, this indicator offers an alternative option for testing the plausibility of simulation outcomes, through comparing the simulated relationships between open space area ratio and total unit density of urban regions with actual and historical observations. Testing simulation outcomes against strong empirical relationships has previously been advocated (e.g. for Zipf's law, see de Nijs, 2009) but is yet to represent common practice in land-use simulation.

The proposed indicator toolset can be further refined by combining the open space data set with information on accessibility or population density to, for example, limit the analysis to open space that can be reached within a fixed (travel) distance (e.g. a maximum of 15 min by foot or bicycle as reported by Grahn & Stigsdotter, 2003), or express the number or size of open space units available per person. Adding such variables would further address the fragmentation bias of open space as they facilitate consideration of the strategic spatial qualities of all open space, including smaller isolated spaces within the urban fabric. Another option is to extend the combined graphical indicator of open space development with statistics about the size distribution of spatial units. Indeed, the area of single units offers additional information on the nature of new developments, e.g. large new open areas indicate dissection processes, whereas new small open areas indicate isolation/inclusion processes. Furthermore, the area of new isolated built-up area units can be determined to understand the type of dispersed development that is occurring.

When applying the indicators at the local, city scale it is critical that study areas have similar sample area dimensions (extent) and location criteria (e.g. centred around the historical core of population centres, as was the case in this study), because the metrics used are more sensitive at this scale (see e.g. Saura & Martinez-Millan, 2001 for an evaluation of metric sensitivity in relation to map extent). For example, a larger sample area can imply the complete or partial inclusion of surrounding cities, while a shift in the sample area can cause the exclusion of parts of the main city. We favour the definition of fairly large regular shapes (squares) around urban cores as these are less likely to suffer from the Modifiable Areal Unit Problem (MAUP) than irregularly shaped administrative zones (for a more extensive discussion on this issue in urban development analysis, see Jacobs-Crisioni, Rietveld, & Koomen, 2014.) Furthermore, the level of spatial and attribute generalisation can have a profound effect on the results of fragmentation analysis because a stronger generalisation will tend to result in lower numbers of spatial units. Scales and mapping procedures, including generalisation procedures of the original source data, should therefore be as similar as possible.

By far the biggest uncertainty in the classification and delineation of open space in our analysis is caused by inconsistencies in the time series of the included spatial datasets, which originate from the various base data sets that were incorporated and created through different methods and resolutions. These inconsistencies are certainly prominent in the oldest land-use maps and the simulated patterns for 2040 included here. In particular, simulated land-use patterns are likely to present views on future land-use patterns that are the result of methodological and data treatment choices in the simulation process (Dendoncker, Schmit, & Rounsevell, 2008; Käyhkö & Skånes, 2006). While we have tried to limit the influence of these inconsistencies by applying specific classification and transformation operations, we are aware that they may still influence the results. However, we expect that the changes in large-scale urban development over the long study period are strong enough to partially compensate for the errors introduced by data inconsistencies.

Data inconsistencies are likely to hamper the application of the proposed indicator sets to study long-term open space dynamics in other case study areas, too. Commonly applied datasets such as CORINE and PELCOM underestimate urban land-use classes in predominantly agricultural areas (Fina & Siedentop, 2008; Schmit, Rounsevell, & La Jeunesse, 2006), limiting their use for detailed assessment of changes in open space (Herzog & Lausch, 2001). The recent advent of fairly detailed and consistent time series of historic land-use change in Europe (Fuchs, Herold, Verburg, Clevers, & Eberle, 2015) and human settlement patterns around the globe (Pesaresi et al., 2016) may help overcome these challenges and facilitate analysis of open space dynamics in different socioeconomic contexts. In combination with the latter data set, the presented conceptual model of open space development and associated indicator set can be used to capture the more recent but much faster urban development processes that are currently occurring in the urban agglomerations of Asia and Africa.

Acknowledgements

Johan van der Schuit and Kees Schotten from PBL Netherlands Environmental Assessment Agency are thanked for kindly providing additional historical land-use data and Roland van Soest from Geodesk Wageningen UR for allowing us the use of the post-processed versions of the original historical land-use data for this research.

Appendix A. Geodata sources

Historical land-use data pre-processed into two major classes, built-up area and open area, have been acquired for the available years 1900, 1930, 1960, 1970 and 1980 from the Netherlands Environmental Assessment Agency (*Planbureau voor de Leefomgeving*, PBL) and (for all land-use classes) for 1989, 1996, 2000, 2006 and 2010 from Statistics Netherlands (*Centraal Bureau voor de Statistiek*, CBS). Table A gives an overview of the original data sources and main characteristics of the historical data used.

Table A
Geodata sources.

Title – description	Year	Format	Scale / minimal mapping unit	Source
Urban built-up area Netherlands derived from Historical land use Netherlands (HGN). Compiled from analogue topographical maps 1:10,000	1900 1960 1970 1980	Vector / polygons	1:10,000 / 50 m	Derived product from PBL Original product from Alterra Wageningen
Urban built-up area Netherlands. Compilation source unknown	1930	Vector / polygons	Unknown	PBL (originally from RPD – 'Rijksplanologische Dienst')
Land use Netherlands	1989	Vector / polygons	1:10,000 / Roads 2 m wide	CBS
Digital land-use map based on aerial photographs 1:10,000	1996 2000 2006		Canals/rivers/ditches: 6 m wide	CBS and Dutch Cadastre via DANS (https://easy.dans.knaw.nl/ui/datasets/id/easy-dataset:47152)
Non built-up areas are defined as areas in which grids of 500 × 500 m have fewer than 25 addresses per grid	2010		Buildings: 9 m^2	Dutch National SDI (PDOK) – https://www.pdok.nl/en/products/pdok-downloads/atomfeeds
Global Economy (GE) land-use scenario	2040	Raster	100 m	SPINlab, Vrije Universiteit Amsterdam (see Riedijk et al., 2007).
Population per municipality	all	Table	Municipalities	CBS census 1930, population density per municipality. Censuses 1795–1971 (CBS); NIWI – KNAW (1998, 2005). Regional statistics (regionale kerncijfers) CBS 1990
Population per place (within municipality) CBS: 'Gemeente op maat'	2008 and 2010	Table	Municipalities	http://www.cbs.nl/nl-NL/menu/themas/dossiers/nederland-regionaal/publicaties/gemeente-op-maat/default.htm
Population per 100 m grid (number of inhabitants)	2000 to 2014	Vector / polygons	100 × 100 metres	CBS(statistische gegevens per vierkant), 2014
Households	all	Table	National	Population, households and population development from 1899 (CBS)
National Historical roads (Nationaal Historisch Wegenbestand)	1960 1970 1980 1990	Vector / polylines	1:100,000	Department of Waterways and Public Works (Rijkswaterstaat) / PBL. http://nationaalgeoregister.nl/
National roads 2000 and 2010	2000 2010	Vector / polylines	1:100,000	Data/ICT service of Department of Waterways and Public Works (Data & ICT Dienst Rijkswaterstaat -DID)

The original historical land-use data from the years 1900, 1960, 1970 and 1980 were compiled digitally in a GIS on the basis of analogue topographical maps 1:10,000 (Kramer, 2005–2010) and processed by PBL to extract only the built-up area, i.e. the land-use classes built-up area, green houses and the mixed class built-up area and roads. The latter mixed class was processed by PBL separately to isolate the built-up area from the roads. As there is currently no historical land-use data available for the period between 1900 and 1960 of similar quality we use an additional more generalised dataset with the extracted built-up area from the land use of 1930 to fill the gap between these years. This dataset has also been provided by PBL but was produced separately by the predecessor of PBL (RPD – Rijksplanologische Dienst).

The reliability of classification and spatial extent of urban area in the 1900 and 1930 maps is uncertain. If we compare these maps with other map sources such as the maps produced and published by the cultural heritage agency of the Netherlands[1] large differences can be noted (see Fig. A.1). However, if visually compared with a more recent growth map of Amsterdam based on a combination of the topographical base map from the Netherlands (1:10,000) and the key register of addresses and buildings ('BAG') for the year 1900, our processed version of the original land-use map appears more accurate (see Fig. A.2). From 1989 onwards all original land-use data have been derived digitally in a GIS from CBS.

All geodata operations and spatial analysis (see appendix B and C) have been carried out with GIS software from ESRI (ArcGIS 10.2.2 and Spatial Analyst Extension, ArcGIS Modelbuilder and Python scripting module). All geodata is or has been projected to the national coordinate system

[1] https://landschapinnederland.nl/verstedelijkingskaarthttp://rce.webgispublisher.nl/Viewer.aspx?map=VerstedelijkingNL

'Rijksdriehoekstelsel' (RD_New in ArcGIS).

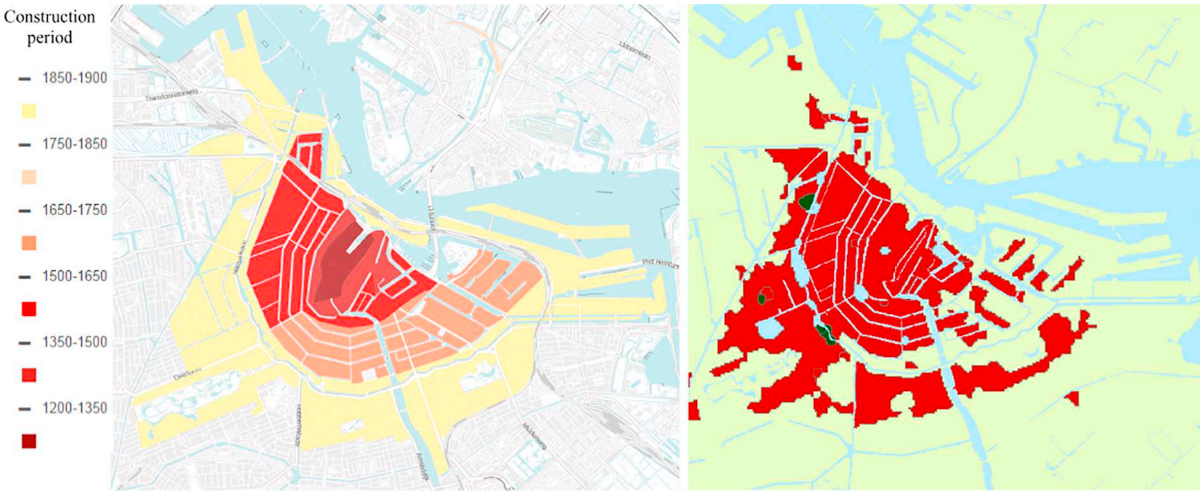

Fig. A.1. (left) Urban extent Amsterdam in 1900 according to cultural heritage agency and (right) processed version (by authors) of original map by PBL and HGN © WUR – Alterra.

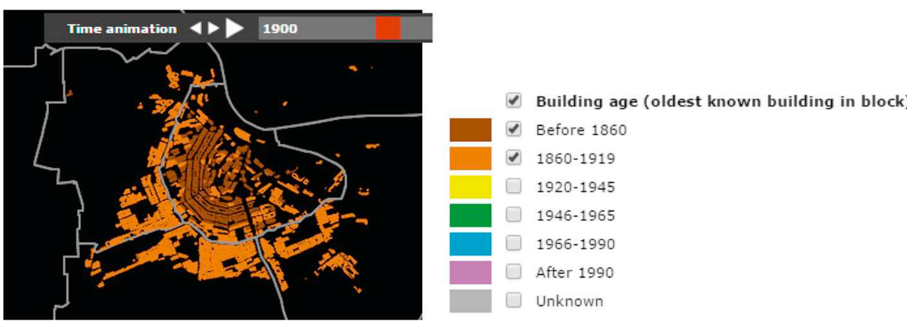

Fig. A.2. Urban extent Amsterdam in 1900 according to combination of topographical map and key register of addresses and buildings in mapservice municipality Amsterdam (URL: http://maps.amsterdam.nl/bouwjaar).

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Appendix B. Land-use reclassification and harmonisation

All historical datasets listed in Appendix A have been reclassified to built-up or open land using the reclassification scheme listed below (Table B). This classification coincides with the pre-processed classes by PBL Netherlands Environmental Assessment Agency. In a final step of the data preparation procedure all polygon layers or raster layers of lower resolution have been converted to a raster cell resolution of 25 m for further processing.

Table B
Reclassification scheme 1900–2010.

Land-use classes			Reclassed to
1900–1980	1989–2010	2040	
Buildings and roads	Not elevated and/or extensive infrastructure (railways, airports, local to main roads)	Infrastructure	Open
	National roads / highways		Built-up
Buildings and roads	Residential	Urban area	Built-up
Buildings	Industrial	Commercial / Industrial / Seaport	Built-up
	Retail and catering		Built-up
	Public facilities		Built-up
	Public and socio-cultural facilities		Built-up

(*continued on next page*)

Table B (*continued*)

Land-use classes			Reclassed to
1900–1980	1989–2010	2040	
Other	Other urban classes (construction or extraction sites, semi-paved terrains, dumping and wreckage grounds, cemeteries)	Building lot	Open
	Recreation (day trips and accommodation)	Recreation single day / stay	Open
	Parks and public gardens		Open
	Sport parks		Open
	Allotment gardens		Open
Greenhouses (from 1960)	Greenhouses	Greenhouse horticulture	Built-up
Other agricultural use	Other agricultural use (grassland, arable land / bare ground)	Grassland / Perennial crops / Arable land	Open
Forest	Forest		Open
Dry natural area	Dry natural area (heath, moorland, drift sand and sandbars)	Nature dry / wet	Open
Wet natural area (swamps)	Wetlands		Open
Water	Large water bodies (North Sea, IJsselmeer)		Large open water
Water	Rivers, canals and smaller water bodies (lakes, ponds and other water)	Water	Open

A number of relevant differences in classification and scales between the different datasets are known. For example, until the year 1996 the Dutch Statistics office assembled the land-use maps on the basis of detailed maps delivered by all municipalities in the Netherlands. From 1996 onwards the Dutch Statistics office constructed the land-use map independently on the basis of the most current Dutch topographical map, scale 1:10,000 in combination with aerial photography. Another difference is caused by the classification of airports and airstrips in the original land use maps up to 1980 as built-up area and the subsequently post-processing step by PBL in which the built-up area was formed by the feature envelope of all airport features. These areas, except parts that are classified as built-up area in the 1996 land use map, we have re-classified to open spaces in a separate post-processing step. Because of the methodological differences in data collection and map construction between the different years some relatively small areas (< 5 ha) of built-up land show up as open area in more recent maps. A harmonisation procedure has been carried out to replace built-up area with open space in the datasets where these areas consisted of open area in more recent datasets (until 1996).

We make an exception on this decision rule for the year 1930. Between 1930 and 1960 we find more and larger areas that changed from built-up to open space. As we can not be sure this is only the consequence of differences in classification and mapping, also with the second world war in between, we have decided to maintain all the built-up area from 1930 (except for areas that were classified as parks and public gardens after 1930).

As we do not consider the inter-urban not-built-up linear spaces such as roads and canals between blocks of houses or other buildings, as open space, we need to merge and dissolve these spaces with the surrounding built-up area. The applied procedure is described in the last paragraph of Section 4.1 in the main text. Because we do not consider national infrastructure as open space we have constructed a separate layer with the geometrical outline of national infrastructure within 100 m distance of built-up area units from the same building period. We merge this layer with the built-up layer from the same year prior to carrying out the buffer operations described in the main text.

We follow a separate reclassification scheme for the two land-use scenarios of 2040 which are mapped in a lower spatial (100 m) and attribute (15 classes) resolution than the historical datasets. As a consequence these maps contain a mixed land-use class urban area which includes local roads, water surfaces and different type of open spaces such as parks, public gardens and sport fields. To extract the open spaces in this class we replace urban area in these maps by open area where these areas coincide with historical parks or green spaces established before 1990 and still remained as open space until 2010. The motivation for following this approach is our assumption that older green space and parks closer to the historical centre have higher chances for conservation. So we assume that their survival until 2010 can be prolonged until 2040. Another correction we make concerns existing major infrastructure (highways) in 2010 that is not well simulated by the model. The 2010 infrastructure is therefore superimposed to the 2040 map.

The generalisation process for the 2040 data has been carried out using the 'boundary clean' tool in the ArcGIS 10 software. The boundary clean tool is a raster based tool used to smooth ragged edges between zones using a method of expanding and shrinking on a relatively large scale on the basis of size ranking priority. By choosing the ASCEND option small open spaces, mostly single 100 m grid cells, surrounded by built-up space get more chance to become invaded by their surroundings (i.e. dissolved to built-up space), while small built-up area units surrounded by open space become more evident.

As a final step we apply a correction factor to the number and areas of spatial units in the processed scenario map of 2040 because the land-use model has a tendency to concentrate the projected land use in relatively small number of units. To determine this correction factor we apply the model to simulate the year 2000 and compare the results with observed land use in that year. The observed differences in average size and total number of open and urban spaces are used to construct a proportional correction factor for the 2040 result.

Appendix C. Development combined indicator open space area ratio / total unit density

We construct this indicator from two spatial metrics, one for measuring the area of open space in relation to the totally available area (open space ratio) and one for measuring the total number of open and built-up area units for each study area (total unit density). The primary output of this map based indicator is in the form of tables.

To enable the counting and area determination of separate units of open and built-up space the connectivity of each cell class has been defined by carrying out a 'region group' (raster) analysis in ArcGIS. For built-up cells to spatially connect within the same zone an eight neighbors rule (a 'Moore' neighborhood) is used. This implies connectivity between built-up unit cells is effectuated in case raster cells form direct neighbors of each other in straight or diagonal direction.

We create the layers with connected open spaces by multiplying the built-up raster layer (open space = 1, built-up space = 0) with the rasterised national roads layer (roads = 0, no roads = 1). By carrying out another region group analysis using a 4 neighbors rule, separated open spaces are defined. This implies connectivity between open raster cells is only effectuated in case raster cells form direct perpendicular neighbors of each other.

By applying these selection rules open space is more quickly isolated than built-up space which corresponds better with human visual perception of open space (open space that seems visually isolated might still have a physical street connection to adjacent open spaces).

After producing the built-up and open spaces layer for each year spatial statistics are derived by carrying out a series of 'zonal statistics as table' operations (SUM, VARIETY) in ArcGIS for each of the distinguished analysis zones. This way the total area, the total number of built-up and open space units is calculated for each year and joined and exported into one spreadsheet for each of the distinguished scale levels. Subsequently, graphs are constructed that show the spatial development of area, number and derived statistics of built-up and open spaces through time and different levels of spatial aggregation.

Finally, from the area of open space and the total number of built-up and open spaces, respectively the area ratio of open space and total space and the unit density of all combined open and built-up spaces per 100 km^2 is calculated.

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